

The complex interplay of dust and star light in spiral galaxy discs

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Abstract Interstellar dust grains efficiently absorb and scatter UV and optical radiation in galaxies, and therefore can significantly affect the apparent structure of spiral galaxies. We discuss the effect of dust attenuation on the observed structural properties of bulges and discs. We also present some first results on modelling the dust content of edge-on spiral galaxies using both optical and Herschel far-infrared data. Both of these results demonstrate the complex interplay of dust and star light in spiral galaxies.

1 Introduction

It has been known for a long time that interstellar dust grains are an important component of the interstellar medium in galaxies: they efficiently absorb and scatter UV and optical radiation, play an important role in the chemistry of the ISM and are the dominant source of far-infrared and submillimetre emission. Detailed knowledge of the quantity, spatial distribution and physical properties of the dust in spiral galaxies is still controversial in many ways. For several decades after the work by Holmberg (1958), it was assumed that spiral galaxies were optically thin for optical radiation. This conventional viewpoint was questioned in the late 1980s and early 1990s by several teams, including Disney et al. (1989), Valentijn (1990) and Burstein et al. (1991). These authors came to the conclusion that spiral galaxies are optically thick, even in the outer regions. Around the same time, other teams

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reached completely different conclusions, sometimes on the basis of identical data sets (e.g. Huizinga & van Albada 1992).

In retrospective, three issues conspired to complicate the discussion on the optical thickness of spiral galaxies. The first was observational biases in the classical tests, such as the expected variation of isophotal diameter, mean surface brightness with increasing inclination. It is very difficult to quantify these biases, let alone to circumvent them (e.g. Davies et al. 1993). A second issue that complicated the discussion was the unavailability of reliable far-infrared observations that traced the bulk of the dust mass in spiral galaxies. In particular, almost no far-infrared or sub-millimetre data were available redwards of $100\ \mu\text{m}$, the longest IRAS wavelength. The final and possibly the most important reason why the contrary results were obtained was the simplicity of the models used to analyze or interpret the data. This was convincingly demonstrated by Disney et al. (1989), who showed that simple optically thick models could reproduce the same observations on the basis of which Holmberg (1958) had reached his conclusions.

One of the first to realize that realistic models for dusty galaxies were absolutely needed to investigate the dust content of spiral galaxies was Ken Freeman. He and his Ph.D. student Yong-Ik Byun embarked on the first systematic effort to investigate the complex interplay of dust and star light in realistic models of spiral galaxies, using detailed radiation transfer simulations including both absorption and scattering. The result of this seminal work, presented in Byun et al. (1994), is still a monument in the extragalactic radiative transfer community.

In the past 15 years, the modelling of the interplay between dust and star light in spiral galaxies has been dealt with by many authors. In particular, several groups have developed the necessary numerical codes to solve the radiative transfer problem in extragalactic environments. The most advanced of these codes are not restricted to only absorption and scattering in 2D geometries, but take into account thermal emission by dust, polarization, kinematics and multi-phase dust distributions (e.g. Popescu et al. 2000; Gordon et al. 2001; Misselt et al. 2001; Steinacker et al. 2003; Bianchi 2008). Our group has also developed a 3D radiative transfer code, SKIRT, based on the Monte Carlo method. Its original aim was to investigate the effects of dust absorption and scattering on the observed kinematics of elliptical galaxies (Baes & Dejonghe 2000, 2002; Baes et al. 2000). It has now developed into a mature radiative transfer code that can be used to simulate images, spectral energy distributions, kinematics and temperature maps of dusty systems, ranging from circumstellar discs to AGNs (e.g. Vidal et al. 2007; Stalevski et al. 2010). In particular, the code has been used as the main tool for a detailed investigation of radiative transfer in spiral galaxies (Baes & Dejonghe 2001a, b; Baes et al. 2003). In the remainder of this paper we shortly describe two recent results that demonstrate the complex interplay of dust and star light in spiral galaxies: in Section 2 we discuss the effect of dust attenuation on the observed structural properties of bulges and discs, and in Section 3 we present some first results on modelling the dust content of edge-on spiral galaxies using both optical and far-infrared data.

2 Dust effects on bulge and disc parameters

It has been known for many decades that the presence of dust influences the observed, apparent photometric galaxy parameters (apparent scalelengths, surface brightnesses, luminosities, axial ratios, etc.) and makes it a challenge to recover the intrinsic unaffected parameters. Several authors have investigated these effects using radiative transfer modelling with varying degrees of sophistication and/or geometrical realism. In general, it was found that the importance of dust attenuation varies as a function of wavelength, galaxy inclination and star-dust geometry. In particular, Byun et al. (1994) were the first to convincingly demonstrate that effects of scattering are often counter-intuitive and crucial to properly interpret the effects of dust.

In the last few years, two independent teams have investigated the effects of dust attenuation in bulge and disc components, on their integrated properties, separately, using realistic models of spiral galaxies. Both Pierini et al. (2004) and Tuffs et al. (2004) presented attenuation functions for the individual disc and bulge components of dusty spiral galaxies. They clearly demonstrated that the effects of dust on the bulge and disc components can differ substantially, as a result of the different star-dust geometry. We have aimed to extend this work one stage further. We have embarked on a project to investigate the systematic effects of dust attenuation on the apparent detailed structural properties of discs and bulges simultaneously. We have created artificial galaxy images, using radiative transfer simulations, to mimic the observed structural properties of disc galaxies with classical and pseudo-bulges, and include the effects of dust attenuation in the observed light distribution. By applying 2D bulge/disc decomposition techniques in this set of models, we were able to evaluate what are the effects of galaxy inclination and dust opacity on the results from such decompositions.

Rather surprisingly, we have found that the effects of dust on the structural parameters of bulges and discs obtained from 2D bulge/disc decomposition cannot be simply evaluated by putting together the effects of dust on the properties of bulges and discs treated separately. In particular, the effects of dust in galaxies hosting pseudo-bulges might be different from those in galaxies hosting classical bulges, even if their dust content is identical. Confirming previous results, we find that disc scalelengths are overestimated when dust effects are important. In addition, we also find that bulge effective radii and Sérsic indices are underestimated. Furthermore, the apparent attenuation of the integrated disc light is underestimated, whereas the corresponding attenuation of bulge light is overestimated. Dust effects are more significant for the bulge parameters, and, combined, they lead to a strong underestimation of the bulge-to-disc ratio, which can reach a factor of 2 in the V band, even at relatively low galaxy inclinations and dust opacities (see Fig. 1). The reason for these, at first sight, counter-intuitive results comes from the fact that such decompositions use specific models to fit bulges and discs which cannot accommodate the effects of a dust disc in the galaxy. Therefore, when the model for a component tries to adjust itself when dust is present, this has direct consequences on the model of

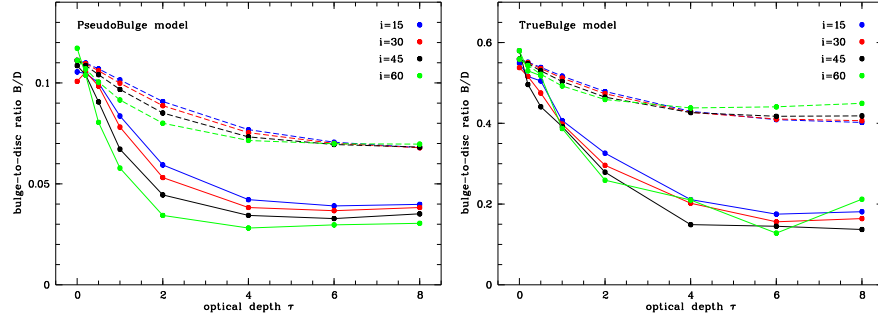


Fig. 1 Dependence of the bulge-to-disc ratio on the V-band optical depth τ . The solid lines represent the apparent bulge-to-disc ratio as derived from the BUDDA bulge/disc decompositions of the dust-affected images. The dashed lines represent the actual bulge-to-disc ratio as determined from the ratio of the input bulge and disc integrated fluxes.

the other component, even if the latter is not directly affected by dust. More details can be found in Gadotti et al. (2010).

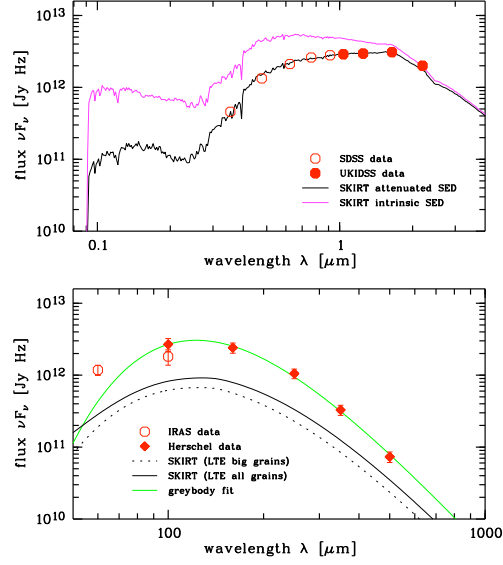
3 The energy balance in spiral galaxies

Apart from more advanced modelling techniques, one of the crucial steps forwards (compared to the early 1990s) in determining the dust content of spiral galaxies is the availability of observations in the far-infrared range between 100 and 1000 μm . Observations in this wavelength range are crucial because they directly trace the smoothly distributed cold dust in spiral galaxies, which is heated to temperatures of some 20 K by the general interstellar radiation field. While the ISO and Spitzer missions have opened up the far-infrared window out to 200 μm , the most important step forward was the launch of Herschel in May 2009. The first results of Herschel imaging of nearby galaxies such as M81, M82 or NGC 4438 are spectacular (e.g. Bendo et al. 2010; Roussel et al. 2010; Cortese et al. 2010).

We are focusing our attention to edge-on spiral galaxies, because they are an important class of galaxies in which the distribution and properties of interstellar dust grains can be studied in great detail. On the one hand, the dust in these systems shows prominently as dust lanes in optical images; on the other hand, surface brightness enhancements ensure that the far-infrared dust emission in edge-on spirals can be traced out to large radii. A self-consistent treatment of extinction and thermal emission, i.e. a study of the dust energy balance, gives the strongest constraints on the dust content of spiral galaxies.

For several edge-on spiral galaxies, the dust distribution has been modeled by fitting realistic radiative transfer models to such optical images (Kylafis & Bahcall 1987; Xilouris et al. 1997, 1998, 1999; Alton et al. 2004; Bianchi 2007). The conclusion of these works is that, in general, the dust disc is thinner (vertically) but

Fig. 2 The optical/NIR (top) and FIR/submm (bottom) spectral energy distribution of UGC 4754. The solid black line in the top panel corresponds to the attenuated SED of the SKIRT model fitted to the SDSS and UKIDSS images, the magenta line is the unattenuated SED. In the bottom panel, the solid black line corresponds to the FIR emission of the model assuming LTE for all grains; the dotted line represents the contribution of the large grains only. Our model significantly underestimates the observed IRAS and Herschel fluxes.



radially more extended than the stellar disc and that the central optical depth perpendicular to the disc is less than one in optical wavebands, making the disc almost transparent when seen face-on. This result seems to be at odds with FIR/submm emission studies, which indicate that spiral galaxies typically reprocess about 30% of the UV/optical radiation (Popescu & Tuffs 2002). When applied to individual edge-on spiral galaxies, it is found that the predicted FIR fluxes of self-consistent radiative transfer models that successfully explain the optical extinction generally underestimate the observed FIR fluxes by a factor of about three (Popescu et al. 2000; Misiriotis et al. 2001; Alton et al. 2004; Dasyra et al. 2005). Several scenarios have been proposed to explain this discrepancy, but a major problem discriminating between these is that the number of edge-on galaxies for which such detailed studies have been done so far is limited, due to the poor sensitivity, spatial resolution and limited wavelength coverage of the available FIR instruments.

We have used Herschel PACS and SPIRE observations of the edge-on spiral galaxy UGC 4754 to investigate its dust energy balance (for more details, see Baes et al. 2010). We build detailed SKIRT radiative models based on SDSS and UKIDSS maps, and use these models to predict the far-infrared emission. We find that our radiative transfer model underestimates the observed FIR emission by a factor two to three (see Fig. 2). Similar discrepancies have been found for other edge-on spiral galaxies based on IRAS, ISO and SCUBA data. Thanks to the good sampling of the SED at FIR wavelengths, we can rule out an underestimation of the FIR emissivity as the cause for this discrepancy. We argue that the most likely explanation for this energy balance problem is that a sizable fraction of the FIR/submm emission arises from additional dust that has a negligible extinction on the bulk of the starlight, such as young stars deeply embedded in dusty molecular clouds. The presence of com-

pact dust clumps can boost the FIR/submm emission of the dust while keeping the extinction relatively unaltered (e.g. Silva et al. 1998; Bianchi et al. 2000; Bianchi 2008). An indication that embedded star forming clouds might be the solution to the case of UGC 4574 is that the discrepancy between our radiative transfer model and the observed FIR SED is stronger at shorter than at longer wavelengths. This implies that warmer dust (such as in star forming regions) is necessary to bring the model in balance with the data.

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